Chapter 1

The Triazine Herbicides: A Milestone in the Development of Weed Control Technology

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Summary

This book is about the revolutionary impact of the triazines herbicides, likely the most important class of agricultural chemicals ever developed. For five decades the triazines have provided weed control in more than 50 crops around the world and have helped farmers boost yields and produce enough food to feed a rising global population. The triazine herbicides, and especially atrazine, are the most well-researched herbicides in history, with thousands of scientific studies on their safety to humans and the environment. Data from studies on the triazines have been evaluated extensively by regulatory authorities around the globe to ensure their safe use.

The first triazine was discovered in 1952 at J.R. Geigy, Ltd. in Switzerland and led to major advances in agricultural practices, basic research, safety testing, and environmental stewardship. Today one or more of the triazine herbicides is registered in more than 100 countries around the globe to provide broad-spectrum weed control in a variety of crops and noncrop sites. They provide application flexibility, are extensively used in conservation tillage programs that are integral to sustainable agriculture, and are important contributors to the management of weed biotypes that have developed resistance to other classes of herbicides.

The triazine herbicides are essential for high-yield, sustainable agriculture. They are critical to integrated pest management (IPM) and conservation tillage practices in corn and other crops – reducing the devastating environmental impact of erosion, reducing fuel costs, and retaining moisture in soil.

Changes in Agriculture and the Importance of the Triazine Herbicides

Since the 1900s, there have been significant improvements in agriculture yields, with average increases ranging from 238% to 811% for corn, cotton, sorghum, soybean, wheat, potato, and tomato (Table 1.1). From an average corn yield of 2.76 metric tonnes/ha during 1950–1959, yields of 8.87 metric tonnes/ha were obtained during 2000–2004. Since the late 1950s, the triazine herbicides have contributed significantly to improvements in yields in crops around the world.

The historical record reveals that herbicides have replaced or reduced the use of hand weeding and cultivation for weed control, with an associated reduction in cost and an increase in yield. Today herbicides are used routinely on more than 90% of the area of most US crops, representing 87 million ha of cropland (Gianessi and Reigner, 2007).

There is a need for continued increases in yields not only to feed a growing world population, but also for greater fuel production (OECD-FAO, 2007). For example, US ethanol production, predominately based on corn, is expected to double between 2006 and 2016 (Figure 1.1). By 2016, ethanol is expected to represent a full one-third of corn production. Corn used for fuel in China is expected to increase from 3.5 million tons in 2006 to 9 million tons in 2016 (Figure 1.2). Ethanol production in Brazil is predominately based on sugarcane and is expected to increase by 145% between 2006 and 2016 (Figure 1.3).

The first triazine was discovered in 1952 at J.R. Geigy, Ltd. in Switzerland. Today one or more of the triazine herbicides are registered in more than 100 countries around the world and are key to the production of more than 50 crops. Table 1.2 shows the major triazine herbicides today and their key uses.

The use volumes in the United States by major crops are shown in Figure 1.4 for atrazine and Figure 1.5 for simazine.

Table 1.1 US average yield in metric tonnes/ha and percent change for 10-year periods through 1999 and for the 5-year period of 2000 through 2004[a]

Period	Corn for grain	Wheat for grain	Sorghum for grain	Soybean for beans	Lint cotton	Potato	Processing tomatoes
1900–1909	1.69 (100)[b]	0.97 (100)[b]	NA	NA	0.207 (100)[b]	6.4 (100)[b]	NA
1910–1919	1.63 (96)	0.95 (98)	NA	NA	0.206 (100)	6.5 (102)	NA
1920–1929	1.69 (100)	0.94 (97)	NA	NA	0.183 (88)	7.5 (117)	10.1 (100)[b]
1930–1939	1.51 (89)	0.89 (92)	0.80 (100)[b]	1.08 (100)[b]	0.231 (112)	7.6 (119)	9.4 (93)
1940–1949	2.13 (126)	1.15 (119)	1.10 (138)	1.27 (118)	0.298 (144)	11.3 (177)	13.2 (131)
1950–1959	2.76 (163)	1.32 (136)	1.49 (186)	1.44 (133)	0.406 (196)	18.5 (289)	24.0 (238)
1960–1969	4.46 (264)	1.78 (184)	3.00 (375)	1.67 (155)	0.536 (259)	22.9 (358)	36.8 (364)
1970–1979	5.59 (331)	2.11 (218)	3.39 (424)	1.88 (174)	0.532 (257)	27.8 (434)	48.4 (479)
1980–1989	6.65 (394)	2.41 (248)	3.75 (469)	2.04 (189)	0.647 (313)	31.8 (497)	59.2 (586)
1990–1999	7.76 (459)	2.60 (268)	4.12 (515)	2.47 (229)	0.725 (350)	37.0 (578)	73.2 (725)
2000–2004	8.87 (525)	2.75 (283)	3.95 (493)	2.58 (238)	0.79 (381)	42.8 (669)	81.9 (811)

[a] This table has been modified and updated from Warren (1998) as averages from USDA National Agricultural Statistics Service data.
[b] The numbers in parentheses are percentages of increases or decreases based on the average yields of the crops in the first decade given.

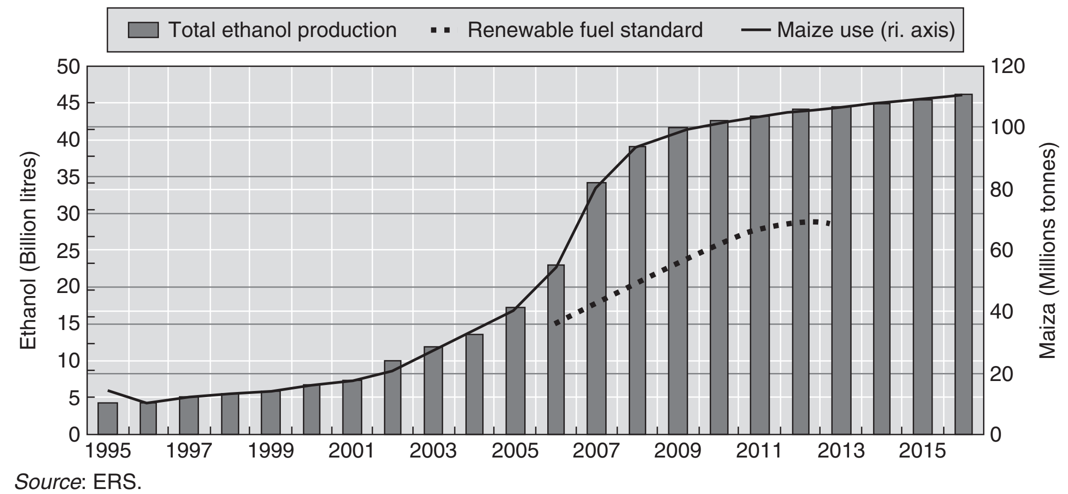


Figure 1.1 Expansion of US ethanol production and corresponding use of corn (maize) (figure from OECD-FAO).

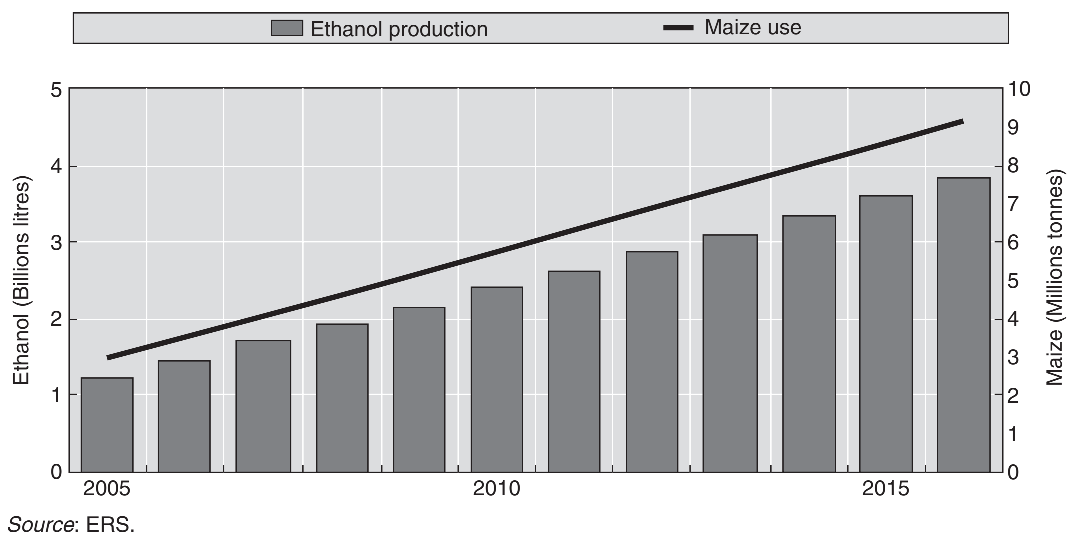


Figure 1.2 Expansion of Chinese ethanol production and corresponding use of corn (maize) (figure from OECD-FAO).

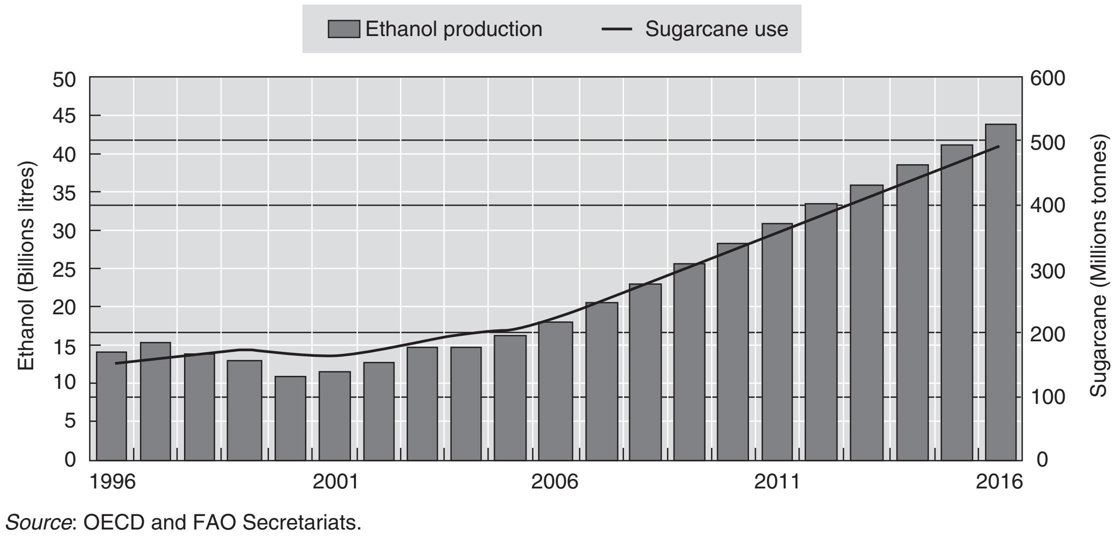


Figure 1.3 Expansion of Brazil ethanol production and corresponding use of sugarcane (figure from OECD-FAO).

Table 1.2 Major triazine herbicides and a partial listing of key uses

Triazine herbicide	Uses
Ametryn	Sugarcane, corn, pineapple
Atrazine	Corn, sorghum, sugarcane
Hexazinone	Alfalfa, sugarcane, forestry, noncropland
Metamitron	Sugarbeet, other beet crops
Metribuzin	Sugarcane, potato, soybean
Prometon	Noncropland
Prometryn	Cotton, celery
Simazine	Corn, citrus, grape, apple, almond, walnut, peach, filbert, pear
Terbuthylazine	Corn, sorghum, grape
Terbutryn	Sugarcane, cereal

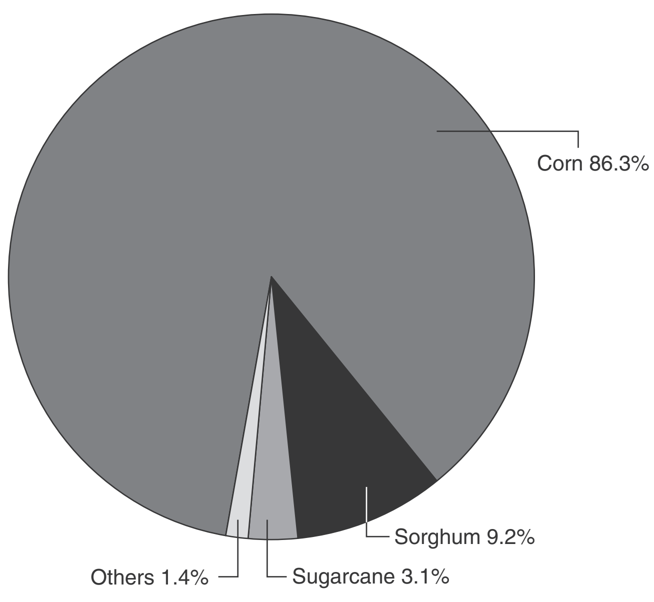


Figure 1.4 Average atrazine use by crop in the United States for 2000–2002 (Doane Marketing Research, Inc.).

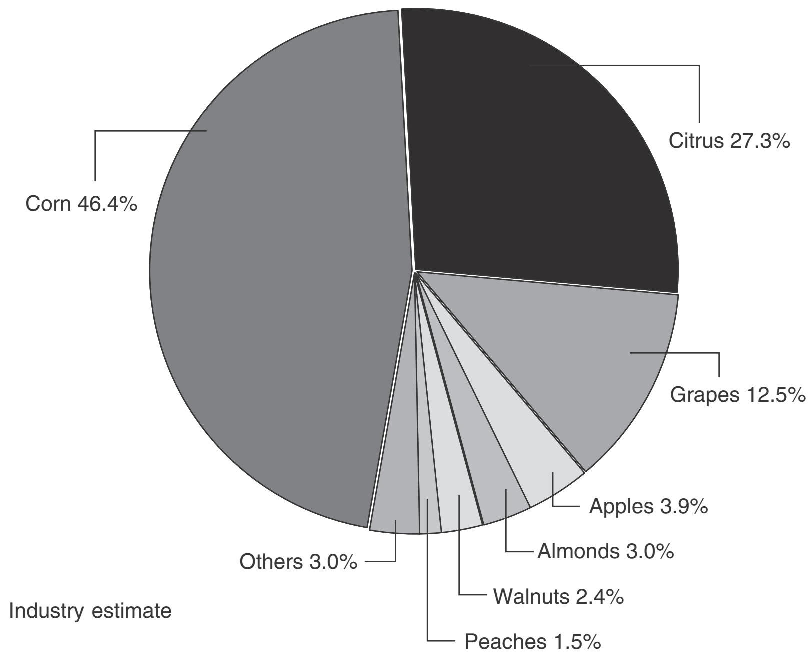


Figure 1.5 Average simazine use by crop in the United States for 2000–2002 (Doane Marketing Research, Inc.).

Table 1.3 Major corn production countries in the world (thousands of metric tonnes)[a]

Country	2003/2004	2004/2005
United States	256 278	299 917
China	115 830	128 000
Brazil	42 000	37 500
Mexico	21 800	22 000
Argentina	15 000	19 500

[a] US Department of Agriculture (USDA) Foreign Agricultural Service (2005).

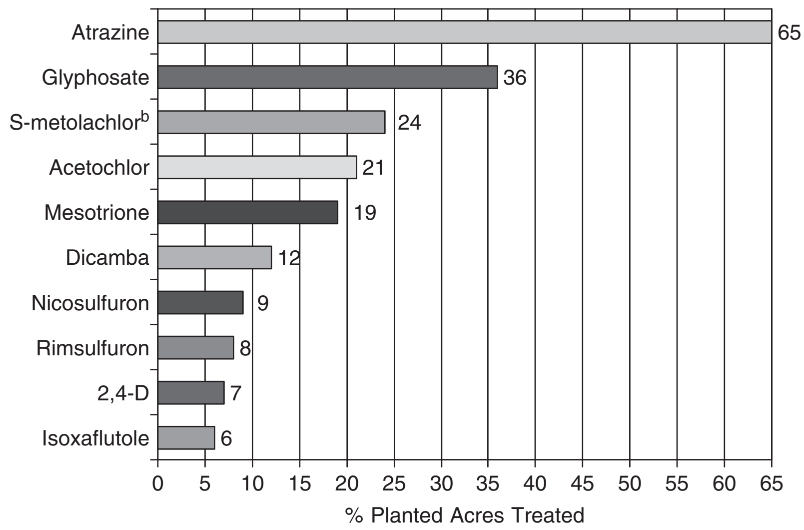
Atrazine is by far the mostly widely used of the triazines, and corn is its major crop use. Table 1.3 shows the top five corn-producing countries in the world. Atrazine is a critical component in the herbicide programs of each of these countries.

One of the reasons the triazines are so important in corn and other crops around the world is their application flexibility and their ability to mix with other herbicides for broad-spectrum weed control. Figure 1.6 demonstrates the relative importance of atrazine in corn compared to other herbicides.

Using atrazine again as an example, Table 1.4 shows a list of nontriazine herbicides used in US corn and the percentage of acres treated with nontriazines that also receive an atrazine treatment.

Many of the active ingredients in Table 1.4 were developed to be atrazine alternatives, but are more valuable to the farmer and provide broader-spectrum weed control when used with atrazine. Specifically, the broadleaf products 2,4-D, bromoxynil, clopyralid, dicamba, flumetsulam, halosulfuron, mesotrione, and prosulfuron are combined with atrazine on 69–82% of their acres. The grass products, *S*-metolachlor, acetochlor, dimethenamid, and nicosulfuron are used with atrazine on 87–97% of their acres. Even the nonselective products glyphosate and glufosinate that are used in genetically modified corn also use atrazine on a large percentage of their acres. Through the use of atrazine with the above herbicides, the average application rate of atrazine in the United States has declined from approximately 2 lb/A (2.24 kg/ha) in 1984 to 1.1 lb/A (1.24 kg/ha) in 2005.

Just as atrazine is important in corn, simazine is a pre-emergence triazine that provides broad-spectrum residual weed control in many of the important fruit and nut crops when applied either alone or in combination with a contact product such as glyphosate to control weeds at the time of application (Figure 1.5).



[a] Based on data from Doane Market Research.
[b] Also includes metolachlor products.

Figure 1.6 Top 10 corn herbicides in United States in 2005 as base acres treated (% of planted acres).[a]

Table 1.4 Percentage of the corn base acres treated with nontriazine herbicides that are also treated with atrazine in 2005

Herbicide	Also treated with atrazine (% acres)
2,4-D	69
Acetochlor	87
Bromoxynil	81
Carfentrazone	80
Clopyralid	73
Dicamba	70
Dimethenamid	97
Flumetsulam	73
Glufosinate	64
Glyphosate	45
Halosulfuron	74
Imazethapyr	51
Isoxaflutole	66
Mesotrione	82
Nicosulfuron	70
Pendimethalin	74
Primisulfuron	76
Prosulfuron	82
Rimsulfuron	72
S-metolachlor	89

[a] Based on data from Doane Marketing Research.

Environmental Benefits of the Triazines

The triazines provide excellent residual pre-emergence weed control and can also be applied with burndown products for control of existing vegetation in no-till or conservation tillage programs. Some of the triazines, such as atrazine and metribuzin, can be used early post-emergence for control of broadleaf weeds and grasses. These unique biological properties of the triazines enable farmers to use no-till and conservation tillage systems that greatly reduce soil erosion and minimize the damage erosion and pollution cause to our lakes, rivers, reservoirs, and water supplies.

Much of today's understanding of the importance of conservation tillage in agriculture began with the US Dust Bowl of the 1930s, an event largely precipitated by extensive plowing to convert grassland acres to wheat and other crops. Though conventional tillage practices were used successfully during times of adequate rainfall, after several droughts, plowing promoted significant wind erosion (Worster, 1979). On April 14, 1935, the powder-dry soil of the

Table 1.5 Estimates of annual off-site damage from soil erosion by damage category in the United States[a]

Damage category	Off-site damage in $ (millions)
Freshwater recreation	2080
Municipal and industrial use	1196
Water storage	1090
Flooding	978
Municipal water treatment	964
Navigation	749
Marine recreation	599
Roadside ditches	535
Marine commercial fishing	390
Irrigation ditches	118
Freshwater commercial fishing	60
Steam power cooling	24
Total	8783

[a] From Riboudo, 1989.

Table 1.6 Conservation tillage in the United States as a percent of total crop acres[a]

Tillage system	1990	1996	2004
No-till	6.0	14.8	22.6
Ridge-till	1.1	1.2	0.8
Mulch-till	19.0	19.8	17.4
All conservation tillage	26.1	35.8	40.7

[a] Conservation Technology Information Center (2004).

Great Plains created what was described as a ‘black blizzard’ (Hurt, 1977, 1981). The disastrous events of the Dust Bowl led to the US Soil Erosion Service Act of 1935, which declared soil erosion a national menace and directed the US Department of Agriculture to establish the Soil Conservation Service (Wehrwein, 1938).

Soil erosion continues to be one of the greatest threats to the sustainability of agriculture around the world. Erosion caused by water and wind reduces rich topsoil and crop yields. Soil erosion also produces a variety of adverse off-site impacts, including increased sedimentation of lakes and streams and transport of nutrients and pesticides to surface waters (Ribaudo and Johansson, 2006) (Table 1.5).

Due to the adoption of conservation tillage systems by farmers around the world, great strides have been made to reduce erosion and its adverse impacts. Using herbicides in conservation tillage has significantly reduced topsoil erosion by more than 50% (Ray and Guzzo, 1993) and in some cases by more than 90% (Laflen *et al.*, 1978). The 2001 National Resources Inventory (Natural Resources Conservation Service, 2003) showed dramatic decreases in erosion in the United States since 1982, much of it due to adoption of conservation tillage. Sheet and rill (water) erosion fell from an average 4.0 tonnes/A/year in 1982 to 2.7 tons/A/year in 2001, a 33% drop. The average wind erosion rate dropped 36% during the same period.

The growth in conservation tillage continues today. In fact, the percentage of no-till acres in the United States grew from 6.0% to 22.6% between 1990 and 2004 as shown in Table 1.6 [Conservation Technology Information Center (CTIC, 2004)]. Conservation tillage was used on more than 40% of all crop acres.

Herbicides, especially the triazine herbicides, have played an essential role in the adoption of conservation tillage by substituting for intensive conventional tillage. For example, atrazine is used on 61.7% of conventional tillage corn in 2004, but on 84.1% of conservation tillage corn (Fawcett, 2007). A 2000 US Doane AgroTrak survey shows that 82% of no-till corn was treated with atrazine, compared to 70% under conservation tillage and 68% under conventional tillage. These results show that atrazine’s importance increases as tillage decreases. It is estimated that erosion would increase by 252 million tonnes/year (Fawcett, 2007) if current conservation tillage practices in US corn reverted to conventional tillage.

By enabling conservation tillage, the triazine herbicides also help significantly reduce fuel use since fewer tillage trips are made across the field. A conventional tillage system consumes about 5.3 gal fuel/A, a mulch tillage system uses about 3.3 gal/A, and no-till uses about 1.4 gal/A (Ayers, 1989; Jasa *et al.*, 1991). Conversion from conventional tillage to no-till for row crops results in a savings that is equivalent to 3.9 gal/A of diesel fuel, for a reduction of 74%.

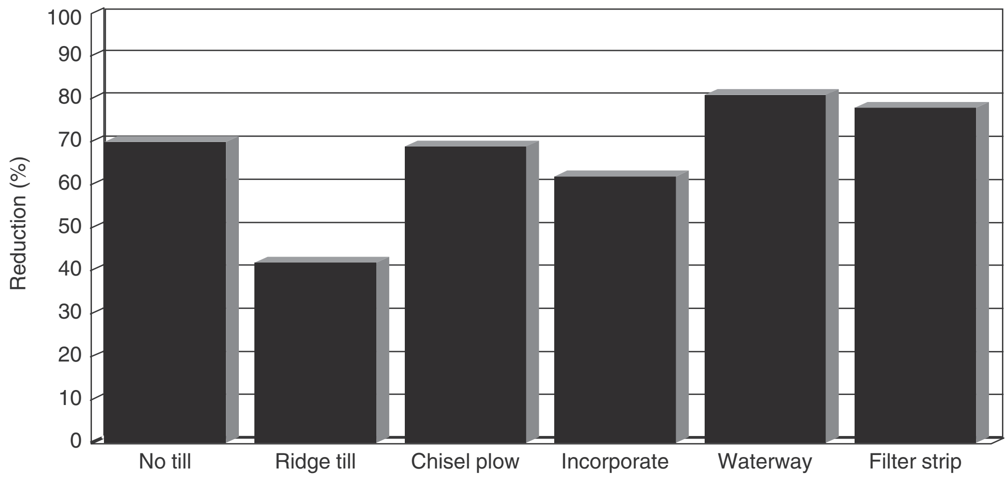


Figure 1.7 Best management practices reduce herbicide runoff (from Ciba-Geigy Technical Report: 10–92).

It is estimated that fuel use would increase by 89 million gallons/year if all corn crop acreage in the United States alone were conventionally tilled (Fawcett, 2007).

Besides saving soil and fuel, the triazines are important tools in conservation tillage systems that conserve soil moisture by reducing evaporation caused by tillage (Fawcett, 2007). Moisture conservation is especially important in the semi-arid areas around the world where grain crops can be grown only by 'fallowing' land and storing soil moisture for all or part of a growing season. When crops are not present and the land is fallow, weeds must be controlled to prevent reductions in soil moisture. The triazines are key to controlling weeds under these conditions and maximize moisture conservation by removing the need for repeated tillage.

Converting from conventional to conservation tillage also can increase the organic matter in soil, rather than continuing to deplete it. During a 10-year study, conservation tillage treatments in a corn–wheat–soybeans–wheat rotation accumulated organic matter at a rate of about 1700 lb/A/year (about 1900 kg/ha/year) faster than conventional tillage treatments (Reicosky *et al.*, 1995). Besides improving soil properties, conservation tillage has the potential to sequester as much as 107 million metric tons of carbon annually in the United States (USDA, 2004).

Conservation tillage and no-till often produce dramatic decreases in water runoff and increases in water infiltration, which results in a reduction not only in soil erosion, but also in pesticide and nutrient runoff into water (Glenn and Angle, 1987; Hall *et al.*, 1991). In several studies of best management practices (BMPs), no-till was shown to reduce herbicide runoff by an average of 70%, while ridge till showed a 40% reduction (Figure 1.7).

Because soil sediment has an extremely negative impact on streams, rivers, and lakes, erosion reductions credited to conservation tillage provide major benefits to aquatic ecosystems. Additionally, conservation tillage benefits wildlife by providing more crop residues for cover, more food sources (grain and weed seed left on the soil surface, as well as a greater number and variety of invertebrates), and less field disturbance.

By making it possible to produce more food and feed on fewer acres, the triazines have provided a direct benefit to the environment. As a result, much of our more vulnerable and erodible land has remained undisturbed as wildlife refuges, wetlands, or other natural ecosystems because the triazines have been critical in increasing yield on acres already in production.

IPM and Resistance Management

The unique action of the triazines also makes them vital to IPM, sustainable agriculture, and resistant weed management strategies. Triazines are an excellent option in IPM programs because of their effectiveness on a broad-spectrum of weeds. In the case of atrazine, its flexibility to be used in early pre-plant, preemergence or postemergence applications, and its utility in combination with other products are also key to IPM. For particularly invasive weeds already known to have resistant biotypes to other herbicides (kochia, common cocklebur, smooth pigweed, Palmer pigweed, tall waterhemp, common waterhemp, and wild sunflower), atrazine is the only product that can be applied either pre- or postemergence and provide effective control.

While newer herbicides are continually being developed, weeds are evolving resistance to these new alternatives very quickly. In addition, weeds that do develop resistance to nontriazine herbicides are generally more difficult

Table 1.7 Role of triazines in management of weeds with resistant biotypes

Family/mode of action	Triazines effective on some resistant biotypes
ACCase Inhibitors (A/1)[a]	Yes
ALS inhibitors (B/2)	Yes
Ureas and amides (C2/7)	Yes
Nitriles and others (C3/6)	Yes
Bipryidiliums (D/22)	Yes
PPO inhibitors (E/14)	Yes
Glycines (glyphosate) (G/9)	Yes
Dinitroanilines (K1/3)	Yes
Thiocarbamates (N/8)	Yes
Synthetic auxins (O/4)	Yes
Organoarsenicals (Z/17)	Yes
Pyrazoliums (Z/8)	Yes

[a] Herbicide Resistance Action Committee (HRAC) group designation, shown in parentheses.

to control than triazine-resistant weeds. Fortunately, the triazines are very effective in controlling many weeds resistant to acetolactate synthase (ALS) and other herbicides, making them an essential component in effective weed management strategies (Table 1.7). The triazines also are very important in controlling the growing number of weeds resistant to glyphosate.

Yield and Economic Improvements Using Atrazine as an Example

The benefits of the triazines in multiple cropping systems range from their application flexibility, effective weed control, soil residual activity, and crop selectivity to their important role in resistance management and conservation tillage. The triazines also have made a major impact on agricultural sustainability and crop yields, as evidenced by the use of atrazine, especially in corn.

The US Environmental Protection Agency (USEPA, 2003a) analyzed the impact of atrazine in corn and found that yields improved on average by approximately 9 bu/A with atrazine as compared to replacement herbicides. Taking into account the yield advantage and alternate herbicide costs, USEPA estimated the value of atrazine in corn at $28/A. This translates into a benefit of $1.6 billion annually nationwide. The USEPA also estimated a 10–40% yield advantage for US sugarcane when atrazine is used, as well as a cost advantage over alternative herbicides.

Corn yields from 236 university trials reported by the North Central Weed Science Society (NCWSS) between 1986 and 2005 showed that atrazine treatments resulted in an average 5.7 bu/A advantage (Fawcett, 2006). These trials used atrazine rates averaging 1.17 lb a.i./A in 1986 and 0.61 lb a.i./A in 2005, which are significantly lower than the maximum label rate. Combining the higher yield from atrazine and the lower herbicide cost with atrazine treatments resulted in added grower income of $25.95/A in 2005.

The yield benefits of atrazine and other triazines vary by tillage type, and field studies have shown that the impact is higher under no-till than under conventional tillage systems (Carlson, 1998).

The National Corn Growers Association in the United States represents more than 32 300 growers from 48 states and each year sponsors a corn yield contest. There are nine production classes varying by geographic region, tillage type, and irrigation. Table 1.8 summarizes the results of the 2006 contest and shows that the impact on yield of treatments containing atrazine in the top five entries in each production class ranged from a 11.5 bu advantage in irrigated corn to a 46.9 bu advantage in no-till/strip till irrigated production. These 2006 results using available tools to maximize yields further support that there are significant advantages with atrazine-containing treatments.

Recent Scientific Reviews and Reregistrations

Hundreds of triazine-containing products continue to be reviewed, registered, and used throughout the world, with regular reregistrations and safety reviews. While several of the triazines have been recently reviewed, the most comprehensive of these reviews in multiple countries involved atrazine and simazine.

In 2006, after a comprehensive science review of chlorotriazines, the USEPA determined 'there is reasonable certainty that no harm will result to the general US population, infants, children, or other major identifiable subgroups of consumers, from the use of simazine, atrazine, and propazine' (USEPA, 2006a, b). The review shows that the chlorotriazines are 'not likely' to cause cancer in humans and that dietary exposure is extremely low, with wide margins

Table 1.8 2006 US National Corn Growers Yield Contest results, including the average yield of the top five in each class, with and without atrazine.[a]

Class	# Grower entries	# of Top 5 entries (by yield) using atrazine	With atrazine		Without atrazine		Average bu/A advantage in top 5 yields with atrazine
			# Entries with atrazine	Average of top 5 yields (bu/A)	# Trials without atrazine	Average of top 5 yields (bu/A)	
Nonirrigated[b]	249	5	177	277.22	72	255.87	21.35
Nonirrigated, seven states[c]	361	5	230	277.93	131	258.23	19.70
No-till/strip till, nonirrigated [b]	236	4	194	270.20	42	257.24	12.96
No-till/strip till, nonirrigated, seven states[c]	155	5	121	277.00	34	250.04	26.96
No-till/strip till, irrigated[d]	183	5	138	316.58	45	269.62	46.96
Ridge till, nonirrigated [b]	47	5	32	241.46	15	213.66	27.80
Ridge till, nonirrigated, seven states[c]	42	4	31	255.35	11	235.53	19.82
Ridge till irrigated[d]	83	4	56	292.66	27	266.24	26.42
Irrigated[d]	263	3	196	298.01	67	286.46	11.55

[a] The 1619 contest entries were not side by side comparisons. 1175 used atrazine as part of their herbicide treatments and 444 did not. Entries with no yield or no herbicide treatments were not included.
[b] Includes continental US states EXCEPT Illinois, Indiana, Iowa, Minnesota, Missouri, Ohio, and Wisconsin.
[c] Includes Illinois, Indiana, Iowa, Minnesota, Missouri, Ohio, and Wisconsin.
[d] Includes all states.

of safety. Additionally, a government-sponsored study conducted by the National Institute of Health, the National Cancer Institute, the National Institute of Health Science, and the USEPA has found no association between cancer incidence and atrazine exposure (Alavanja *et al.*, 2003; Rusiecki *et al.*, 2004; Engel *et al.*, 2005). The USEPA (2007) also determined that atrazine does not impact amphibian gonadal development.

Reviews by the Australian Pesticides and Veterinary Medicines Authority (APVMA) in 1997 and again in 2004 concluded that properly used and applied, atrazine and simazine are safe for humans and the environment [Australian Pesticides and Veterinary Medicines Authority (APVMA), 1997, 2004]. The APVMA also reviewed additional data on potential effects of atrazine on amphibians and concluded that 'taken together, these data indicate that it is unlikely that atrazine is impacting adversely on populations of Australian amphibians at current levels of exposure' (APVMA, 2004).

In 1996 the United Kingdom, which was selected to conduct the scientific review of atrazine for the European Union (EU), concluded: 'It is expected that the use of atrazine, consistent with good plant protection practice, will not have any harmful effects on human or animal health or any unacceptable effects on the environment' (UK Rapporteur Monograph, 1996). In 2000, the United Kingdom for the European Commission also concluded it is not appropriate to classify atrazine as a carcinogen (UK Rapporteur Monograph, 2000).

Much misinformation exists with regard to the European Union's 2003 decision to not reregister atrazine and simazine despite favorable EU reviews of their safety. In 1980, European countries adopted the European Drinking Water Standard, which set an arbitrary limit value of 0.1 ppb for any pesticide in drinking water. This arbitrary limit was applied to all pesticides, irrespective of their safety profiles, and was not scientifically determined. The health-based limit established by the European Union for atrazine based on a preponderance of scientific evidence was 150 times higher. Note that the United Kingdom for the European Union established the health-based limit for water at 15 ppb for atrazine parent. Australia established a 40 ppb health-based limit for parent atrazine and metabolites. In USEPA (2003b) estimated a range of health-based limits (drinking water levels of comparison) for atrazine and its chlorometabolites that ranged from 12.5 to 68 ppb, depending on dietary and water intake estimates for different sub-populations. These health-based limits are more than 125 times to 680 times greater than the arbitrary 0.1 ppb limit adopted by the European Union.

The European Union did recognize that the exceedances of the 0.1 ppb limit in groundwater were based mainly on outdated high rate uses and noncropland uses. Even the 0.1 ppb limit in groundwater would not be exceeded today in most corn-growing regions. Despite these facts, atrazine was not reregistered in the European Union. However, limited uses have been retained until 2007 in some of the member states, such as Ireland, the United Kingdom, Spain, and Portugal (*Official Journal of the European Union (EU) Decision*, 2004). Terbuthylazine, another key triazine herbicide and a product very similar to atrazine, was introduced in Europe almost two decades later than atrazine. As a result, terbuthylazine was never used at high rates or in noncropland applications and remains an important herbicide in Europe for both corn and grape crops. Terbuthylazine also has recently received a favorable science review in the European Union's reregistration process (UK, 2007).

The World Health Organization's International Agency for Research on Cancer (IARC) reviewed atrazine in 1998 and concluded that new toxicology information provides strong evidence that the mechanism responsible for tumors in a specialized type of rat (Sprague–Dawley) is not relevant to humans. As a result, IARC changed its classification of atrazine to 'not classifiable as to carcinogenicity in humans' (IARC, 1999). IARC also reached these same conclusions with regard to simazine.

In 2001, the French Toxicity Research Commission on Pesticide Products cited conclusions by IARC, USEPA, and EU that atrazine is not carcinogenic to humans (French Republic Ministry of Agriculture, 2001). The Commission further stated, 'Considering all these factors, the concentration of the triazines in water, even elevated levels identified in the field both in transitory and localized form, do not represent a public health risk.'

Contribution of Triazines to Agricultural Practices, Basic Research, Safety Testing, and Stewardship

The development of triazine technology resulted in the pioneering of several new agricultural advances, including the development of selective preemergence weed control practices in several crops, the first herbicides with application flexibility (preemergence, postemergence, incorporated, banding, broadcast applications), and the first extensive farmer education programs on weed control. New application techniques using additives were also first developed with the triazines, including surfactants, oils, and liquid fertilizer. New breakthrough formulations discovered with triazine technology included flowable formulations, water dispersible granules, and the first prepacks of herbicides. Packaging advances included the first recyclable containers and the first bulk containers for herbicides.

Advances in science and basic research using triazines as a tool included:

- New developments in the understanding of photosynthesis in plants.
- The first genetic sequencing to explore herbicide resistance.
- Breakthroughs in genetic engineering of plants.
- The first discovery of certain enzymes and metabolites in chemical degradation pathways.
- The discovery of new bacterial genes for pesticide degradation.
- The development of immunoassay methods for herbicides.

Advances in safety testing and chemical risk assessment methodologies attributed to research conducted with the triazines include toxicology mode of action tests, new enzyme and chemical analyses, new methods for analyzing metabolites, exposure monitoring for applicators, water monitoring and analysis methodologies, probabilistic Monte Carlo risk assessment, environmental modeling and mapping, and methodology for amphibian and ecological safety tests.

Widespread adoption of several stewardship practices attributed to the triazines include implementation of conservation tillage practices and many best management practices, including rural well set-backs, vegetative buffers, filter strips, and set-backs from streams and reservoirs. The stewardship practices have been effective and several studies on atrazine levels in water have shown declines in both surface and groundwater. Comprehensive triazine education and research programs to develop and implement best management practices and site-specific watershed management processes have resulted in water quality improvements not only for the triazines, but also for other chemicals, sediment, and nutrients.

Conclusions

The Triazine Herbicides: 50 Years of Revolutionizing Agriculture deals extensively with the research, development, and use of triazine herbicides in the United States, since this is where much of the work on the products was centered.

It is hoped that this book will serve not only as an update and expansion on the agricultural and environmental sciences of the triazine herbicides, but also as a model for the discovery, development, and extensive research needed for future classes of agricultural chemicals and technology. Among the topics it covers are:

- An introduction to the triazines, including their discovery, development, and registration.
- The evolution of weed control in crop production.
- The weed control mode of action of the triazines.
- Benefits of the triazines in crop production.
- Environmental fate of the triazines.
- Human health and environmental risk assessments.
- Environmental stewardship, conservation tillage, and IPM.
- Detailed appendix on triazine nomenclature, chemical structures, and properties.

Today, 50 years since their discovery, the triazine herbicides continue to be critical tools for sustainable and efficient agricultural technology throughout the world.

References

Alavanja, M.C.R., C. Samanic, M. Dosemeci, J. Lubin, R. Tarone, C.F. Lynch, C. Knott, K. Thomas, J.A. Hoppin, J. Barker, J. Coble, D.P. Sandler, and A. Blain (2003). Use of agricultural pesticides and prostate cancer risk in the agricultural health study cohort. *Am. J. Epidemiol.*, 157(9): 800–814.

APVMA (formerly the National Registrations Authority for Agricultural and Veterinary Chemicals) (November 1997). The NRA review of atrazine.

APVMA (October 2004). The reconsideration of approvals of the active constituent atrazine, registrations of products containing atrazine, and their associated labels.

Ayers, G.E. (1989). *Fuel Required for Field Operations*. Extension publication PM-709. Iowa State University, Ames, IA.

Carlson, G. (1998). Cost impacts if atrazine or triazines were not available to growers. In L.G. Ballantine, J.E. McFarland, and D.S. Hackett, eds., *Triazine Herbicides: Risk Assessment*. ACS Symposium Series 683, Washington, DC.: American Chemical Society, pp. 35–48.

Ciba-Geigy (1992). *Reducing Herbicide Runoff: Role of Best Management Practices*. Technical Report: 10-92. Submitted to USEPA.

Conservation Technology Information Center (CTIC) (2004). National Crop Management Survey. www.ctic.purdue.edu/CTIC/CTIC.html

Engel, L.S., D.A. Hill, J.A. Hoppin, J.H. Lubin, C.F. Lynch, J. Peirce, C. Samanic, D.P. Sandler, A. Blair, and M.C. Alavanja (2005). Pesticide use and breast cancer risk among farmers' wives in the agricultural health study. *Am. J. Epidemiol.*, 161(2): 121–135.

Fawcett, R.S. (2006). Two Decades of Atrazine Yield Benefits Research. North Central Weed Society Research Report, Atrazine Yield Data Summary, 1986–1995 and 1996–2005. Average Corn Yield With and Without Atrazine. Prepared for the Atrazine Network for submission to Special Review Division, US Environmental Protection Agency. Available at http://www.ksgrains.com/triazine/NCWSS%20Atrazine%20'96–05'.pdf

Fawcett, R.S. (2007). Triazine herbicide benefits in reducing erosion and fuel use in US corn production. *Southern Weed Science Society Proceedings*.

French Republic Ministry of Agriculture (2001). Triazine-Based Specialties – Intended Decision. Report by the Toxicity Research Commission on Pesticide Products.

Gianessi, L.P. and N.P. Reigner (2007). The value of herbicides in US crop production. *Weed Technol.*, 21: 559–566.

Glenn, S. and J.S. Angle (1987). Atrazine and simazine in runoff from conventional and no-till corn watersheds. *Agr. Ecosyst. Environ.*, 18: 273–280.

Hall, J.K., R.O. Mumma, and D.W. Watts (1991). Leaching and runoff losses of herbicides in a tilled and untilled field. *Agr. Ecosyst. Environ.*, 37: 303–314.

Hurt, R.D. (1977). Dust bowl–drought, erosion, and despair on the Southern Great Plains. *Am. West*, 14: 22–27.

Hurt, R.D. (1981). *The Dust Bowl: An Agricultural and Social History*. Chicago, IL: Nelson-Hall.

IARC Monographs on the Evaluation of Carcinogenic Risks to Humans (1999). World Health Organization International Agency for Research on Cancer. Lyon, France. Volume 13.

Jasa, P.A., D. Shelton, A. Jones and E. Dickey (1991). *Conservation Tillage and Planting Systems*. Cooperative Extension Service, University of Nebraska – Lincoln. Lincoln, NE.

Laflen, J.M., J.L. Baker, R.O. Hartwig, W.F. Buchele, and H.P. Johnson (1978). Soil and water loss from conservation tillage systems. *Trans. Am. Soc. Agr. Eng.*, 21(5): 881–885.

National Registration Authority for Agriculture and Veterinary Chemicals of Australia (November 1999). The NRA review of atrazine: existing chemical review program.

Official Journal of the European Union, Commission Decision. March 10, 2004.

Organisation for Economic Co-operation and Development, Food and Agricultural Organization of the United Nations (2007). *OECD-FAO Agricultural Outlook, 2007–2016*. OECD Publications, France, 87 pp. No. 8853, 2007.

Ray, D.L. and L.R. Guzzo (1993). Environmental overkill: Whatever happened to common sense? Chapter 6, of *Food and Population*. Washington, DC.: Regnery Gateway Publishers, pp. 67–80.

Reicosky, D.C., W.D. Kemper, G.W. Langdale, C.L. Douglas Jr., and P.E. Rasmussen (1995). Soil organic matter changes resulting from tillage and biomass production. *J. Soil Water Cons.*, 50: 253–261.

Ribaudo, M. and R. Johansson (2006). Water Quality: Impacts of Agriculture In K. Wiebe and N. Gollehon, eds., *Agricultural Resources and Environmental Indicators*. Economic Research Service. USDA. *Economic Information Bulletin* 16: 33–41. http://www.ers.usda.gov/publications/arei/eib16/eib16_2-2.pdf

Riboudo, M.O. (1989). *Water Quality Benefits from the Conservation Reserve Program*. Agricultural Economic Report 606. Washington, DC: USDA Economic Research Service. February.

Rusiecki, J.A., A. De Roos, W.J. Lee, M. Dosemeci, H. Lubin, J.A. Hoppin, A. Blair, and M.C.R. Alavanja (2004). Cancer incidence among pesticide applicators exposed to atrazine in the agricultural health study. *J. Nat. Cancer Ins.*, 96(18): 1375–1382.

UK Rapporteur Monograph (1996). Atrazine Report and Proposed Decision of the United Kingdom made to the European Commission under Article 7(1) of Regulation 3600/92. 3 Volumes, 690 pp.

UK Rapporteur Monograph (2000). Addendum to the Report Proposed Decision of the United Kingdom made to the European Commission under Article 7(1) of Regulation 3600/92. Summary, Scientific Evaluation and Assessment.

UK Rapporteur Monograph (2007). Terbuthylazine: The Report and Proposed Decision of the United Kingdom made to the European Commission under Article 8 of 91/414/EEC. August Draft.

USDA Economic Research Service (2004). Economics of Sequestering Carbon in the U.S. Agricultural Sector. TB-1909, April.

USDA Foreign Agricultural Service, Production Estimates and Crop Assessment Division (2005). World Agricultural Production. Corn Area, Yield, and Production, World and Selected Countries and Regions, p. 14.

USEPA (2003a). Atrazine Interim Reregistration Eligibility Decision. Appendix L. Assessment of potential mitigation measures for atrazine. Biological and Economic Analysis Division, Office of Pesticide Programs, October.

USEPA (2003b). Interim Atrazine Reregistration Eligibility Decision (IRED). January.

USEPA (2006a). Memorandum. Atrazine: Finalization of Interim Reregistration Eligibility Decision and Completion of Tolerance Reassessment and Reregistration Eligibility Process.

USEPA (2006b). Triazine Cumulative Risk Assessment. Docket ID Number EPA-HQ-OPP-2005-0481

USEPA (2007). White paper on the potential for atrazine to affect amphibian gonadal development, in support of an Interim Reregistration Eligibility Decision on Atrazine. Submitted to FIFRA Scientific Advisory Panel, October 9–12. Office of Prevention, Pesticides, and Toxic Substances, Office of Pesticide Programs, Environmental Fate and Effects Division. Washington, DC. September 21.

Warren, G.F. (1998). Spectacular increases in crop yields in the United States in the twentieth century. *Weed Technol.*, 12: 752–760.

Wehrwein, G.S. (1938). The remedies: Policies for private lands. *Yearbook of Agriculture*. Washington, DC: USDA, pp. 241–264.

Worster, D. (1979). *Dust Bowl: The Southern Plains in the 1930s*. New York, NY: Oxford University Press.